An approach to quantify manual expertise with collaborative robotics in mind

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***Abstract*— This article presents a quantification approach of manual expertise. The long term goal is to better understand the notion of manual expertise in order to improve the design of collaborative robots, both from a mechanical and control point of view. Based on the existing literature and through exchanges with highly skilled manual operators, we first propose a definition of manual expertise. Based on this definition, we propose quantitative evaluation criteria for three important dimensions of a manual task completion: safety, discomfort and performance. These criteria are evaluated in experiments relying on a physically realistic mock-up of a wood milling task, a highly demanding task in the carpentry domain. This mock-up includes a 7-DOF collaborative robot used both to reproduce the cutting tool wrenches and provide measurement of the wooden part motion. This experimental set-up is used in a training protocol including two groups of 5 novice subjects. This protocol confirms that the proposed approach allows to observe and analyse the handling strategy developed by an operator through training as well as to correlate the type of training to the nature of the developed expertise.**

I. INTRODUCTION

Recent trends in robotics envision the design of a cobotic assistant to relieve industrial operators on multiple aspects of their tasks completion. Enhancement and preservation of workers' health and expertise are among the most promising features that collaborative robots can achieve [1]. These perspectives have mobilized the scientific community, leading to the emergence of technological breakthroughs and to the design of cobotic assistance such as comanipulation by gravity compensation and/or force amplification [2],[3]. Although this type of assistance considerably reduces the drudgery at work, it eludes important aspects of the task, such as safety. In contrast, assistance that improves the safety aspect of the task evades the discomfort aspect [4]. Sometimes, it worsens the performance of the task [5], another essential aspect of the task completion.

After a review of the literature and to the best of our knowledge, the majority of the works devoted to the design of collaborative robotics assistance does not appear to consider at the same time safety, task performance and discomfort. However, as seen in [5] this can be counterproductive. Indeed, improving one of the three dimensions can deteriorate the others. This can hamper the operator and cause a barrier to the acceptability of collaborative robots. To avoid this issue, it is necessary to design assistance that adapts to the operator's requirements. It therefore seems reasonable to introduce a global analysis phase of the task prior to the design of the cobot and its control/assistance modes. This analysis has to be multi-dimensional, accounting at least for the safety, discomfort and performance aspects of the task.

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There are numerous methods for analyzing operators' working conditions, used in particular by ergonomists. The most widely used are certainly posture assessment methods such as RULA or REBA [6]. Although these methods prove to be effective in gauging the degree of worker arduousness when performing a task, they are mainly based on qualitative geometrical considerations. However, as mentioned in [7], it would also be relevant to consider, quantitatively, dynamic factors such as the varying wrenches that the operator undergoes when performing a task. Moreover, these methods evade in their task analysis the worker's safety and performance criteria. Although some methods analyzing working conditions, such as the analysis of work accident statistics [8], refer to safety issues, no method analyzes the performance of an industrial task under the triad safety-discomfort-task performance.

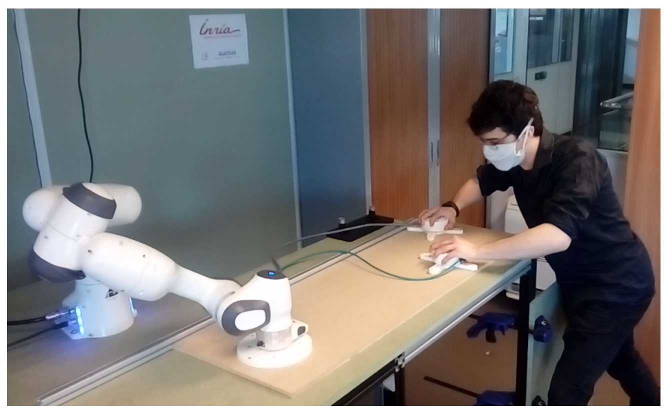

Fig. 1. Subject performing an experiment of a milling task in carpentry using a physically realistic mock-up. The wooden part is being pushed through handles incorporating 6-axis F/T sensors. A 7-DOF collaborative robot is attached to the wooden part and reproduces the cutting forces based on a wood cutting model [9].

In the context of the design of collaborative robots, it seems essential to understand the attention that the operator pays to each of the dimensions of the task completion (safety-discomfort-performance) and to determine which to act on and which to preserve, through the use of a collaborative robot. In addition, this analysis should provide objective indicators used to quantify the provided cobotic assistance both in terms of added value and deterioration of the unassisted dimensions of the task completion. Overall, this should contribute to the improvement of working conditions while preserving the workers manual expertise.

In this paper, we analyze the handling strategy developed by an operator for a wood shaping task in carpentry. Due to its accidental and arduous aspects, and in view of the efficiency requirements in the handicraft sector, this task is a good illustration of the conciliation that the operator must daily perform between safety, discomfort and task performance. To achieve the analysis, we seek to quantify the evolution of the craftsman manual expertise through the three aspects of its behavior during the execution of the task. The objective is twofold:

- confirm that it is possible to analyze the handling strategy developed by an operator through its reconciliation of the safety, discomfort and performance of the task.
- confirm that the operator's manual expertise is developed differently according to the training conditions.

In order to carry out our work, we first explore the concept of manual expertise and its definition in section II-A, and then present our approach for its quantification of manual expertise in section II-B. The pilot task on which this approach is applied and its challenges are detailed in section II-C. We then present the safety, discomfort and performance evaluation criteria chosen for this task in section III-A. In section III-B, we describe the mock-up designed to reproduce the task in a safe and physically realistic way and we then describe the protocol followed to demonstrate our experimental proposals in section III-C. Section IV is devoted to illustrating, commenting and discussing the obtained results: section IV-A is focused on the analysis of the handling strategy developed by the tested subjects while section IV-B focuses on the impact of the training on the learned strategy. Finally, section V brings the conclusion and some perspectives for this work.

II. Manual expertise

A. Manual expertise definition

Depending on their work environment and their experience of the task completion, industrial operators develop a specific expertise [10]. Understanding and quantifying this expertise could help to identify more accurately their need for assistance. This requires to analyze how workers conciliate the safety-discomfort-performance triptych of the task according to his experience.
Through a study on the learning and mastery of chess games, the authors of [10] define expertise as the consequence of a prolonged (10 years) experience and practice of the task. Several works studying expertise [11], [12],[13], agree that this constitutes the reference definition of the concept. Unfortunately, this purely cognitive definition is hardly exploitable for manufacturing tasks with a predominant manual dimension. In the context of manual tasks, quantifiable indicators are desirable to analyze the task-operator couple. Thus, we suggest to observe the gestural or manual expertise, which is the consequence of the cognitive expertise on the task completion.
Some works relate cognition and gesture, particularly in the high-performance sport field [14] where it is important to gauge the evolution of athletes' performances using quantifiable indicators. However, this type of works only develop a one-dimensional analysis of the task-practitioner pair. While getting injured in order to achieve a high level of performance may be acceptable in sports, it is not an option for workers who needs to reproduce the same level of performance every day. Said differently, in the industrial sector, dissociating task performance from safety and discomfort seems unrealistic given their respective importance in the task completion. Sharing this vision, the authors of [15] emphasize the importance of a multi-dimensional analysis of the task, referring to the notion of gestural variability and reflexivity. In their opinion, operators develop an effective and efficient gesture according to their experience of the task by learning how to reconcile its different dimensions.
Based on this literature review, we propose a definition of manual expertise in the industrial framework. We choose to free ourselves from social and psychological aspects, which are considered too abstract.
Definition – *Industrial manual expertise is defined by the operator's ability to optimize his safety, his discomfort and his performance when performing a task. It evolves according to his experience*.
In the following section we propose an approach to quantifying manual expertise for a specific task.

B. An approach to the quantification of manual expertise

To analyze the evolution of an operator's handling strategy according to his manual expertise level and the impact of training on this expertise, it is necessary to complete different phases.
First, we need to define quantitative indicators that evaluate safety, discomfort and performance during the task completion, thus obtaining a concrete quantification of manual expertise. To identify with relevance the physical quantities that impact these dimensions of expertise, this phase must be conducted with the collaboration of professionals, to observe and understand the task completion, its environment and its characteristics. Once chosen, it is important for the analysis that these criteria appear on the same scale in order to facilitate comparisons, interpretations and discussions.
Designing an experiment that gives access to measures of the defined criteria is the second phase of this approach. However, work constraints in the industrial sector are sometimes high: tight production planning, dangerous environment, disturbance due to surrounding tasks... Besides, measuring devices dedicated to the task on site rarely measure quantities related to safety and discomfort. Thus, instrumenting the operator-task pair seems laborious. For this reason, using an experimental mock-up that physically reproduces the process associated to the task completion seems preferable. In addition to ensuring great flexibility in the measurement of physical quantities, using the mock-up ensures workers' safety for tasks that involve dangerous interaction with a machine tool. A collaborative robot can be used to reproduce realistically, and in a controlled manner, the interaction wrenches of the task. In addition, the cobot can be used as a measuring device, which is an advantage in the high-level expert gesture analysis approach.
Once the criteria are defined and measurable, it is necessary to propose in a third phase, an experimental protocol that allows to analyze the evolution of these criteria at an operator's different levels of experience. Indeed, in order to analyze the handling strategy developed by the operator, this protocol should allow to compare the evolution of the three retained indicators between two identified levels of experience for a homogeneous group of subjects. It should also allow to propose two distinct types of training for two different groups in order to compare the evolution of the triptych for both. This can help to analyze the impact of the training on the handling strategy developed by the operator.
In order to assess the relevance of this approach, we apply these phases to the chosen task.

C. A use case for manual expertise quantification

To illustrate our work, we choose wood shaping in carpentry as a pilot task. A wood shaper is a milling tool used to profile wooden pieces (see fig. 2). During the shaping process, a

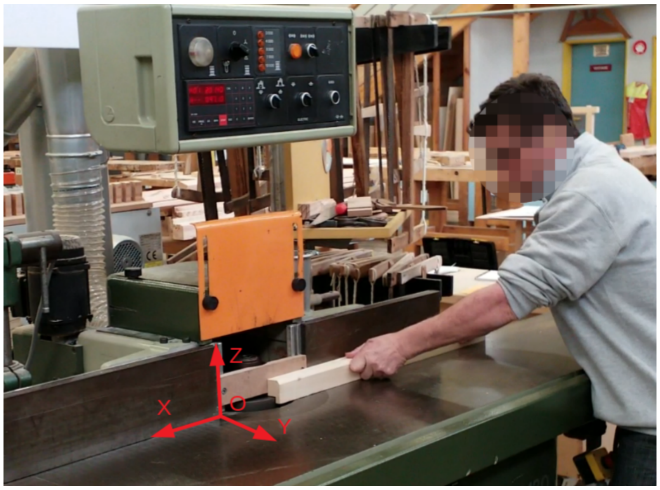

Fig. 2. Illustration of a wood milling task by a trained expert on a wood shaper. The left arm maintains lateral stability while the right arm (hidden on this picture) pushes the part in direction of the cutting tool.

craftsman manipulates a non-homogeneous, anisotropic material in close interaction with the machine tool. He must in most cases move the wooden piece along a rail at a constant speed in order to ensure proper machining quality. It can be tricky to maintain the stability of the wooden part throughout the entire task completion. This can lead to accidents going from bruises to severe cuts on the carpenter's limbs.

According to J. Hester *et al.* [16] studies, among 1200 apprentice carpenters interviewed, 80% already observed a work accident. Moreover, in 2016, the French Institute for Craftsmen's Health and Safety (IRIS-ST) recorded 5118 accidents for 61764 carpenters [17] of which 27% were related to tooling tasks.

As shown in our previous work [5], providing collaborative robotics assistance can potentially reduce the accidental aspect of this task. However, we have observed that acting only on safety disturbs the other dimensions of expertise. Extra safety may indeed require the operator to spend more effort and to machine more slowly. This degrades the performance of the task and increases discomfort. As such, it renders more complex a task that is already, according to the experts, arduous. This can lead to problems of acceptability of the assistance. Thus analyzing the three dimensions of the task completion seems to be essential for the wood shaping, which makes it a good pilot task.

III. Experimental method

A. Assessment Criteria

In order to define relevant indicators that quantitatively evaluate the three dimensions of task completion, it is necessary to analyze all the aspects and constraints of the operator-task couple. To help us determine these criteria, we established a close collaboration with a carpentry training institute. This allowed us to exchange with expert trainers, as well as to understand the task's stakes.

This collaboration allowed the definition of two evaluation criteria per dimension of the triad safety-discomfort-performance which are developed below.

1) Performance:

Time to complete the task – The time required to complete the task is an important indicator of industrial performance [18]. The shorter the machining time, the higher the productivity, therefore we choose it as the first performance criterion

$$p_{b1} = \sum_{i=1}^{N} t_i \tag{1}$$

where t_i, the time necessary to perform the task i and N is the number of successive task completion repetition that is taken into account to quantify the indicator.

Motion fluidity – The collaboration with the carpentry institute instructors helped us understand the importance of machining wood at a constant speed in order not to deteriorate the contour of the wood during the routing process. Thus, we consider the fluidity of the wood movement as a second performance criterion

$$p_{b2} = \sum_{i=1}^{N} \sum_{k=0}^{M_i} \alpha_{x,k}^2 \tag{2}$$

where α_x is the acceleration of the wooden part at instant k along the X-axis (cf. Fig. 2) and M_i is the number of periodic measurements performed for task completion i.

2) Security:

Robustness – During the milling task the operator is subjected to a cutting force tangential to the wooden piece motion (along the Y-axis). This force can be a source of instability and accident, especially when a wooden node appears, where this force is difficult to compensate because it increases suddenly. We therefore consider that the more the operator applies a high intensity of force in the opposite direction ($-Y$), the more robust he is to disturbances. We consider, also that the higher the intensity of the forces applied by the operator in the $-Z$ direction, the more he is able to compensate for a disturbance. Indeed, the application of this force (against the table) generates friction which allows, as shown in [5], to compensate more easily for disturbances, and thus reduces the risk of accidents. The retained robustness indicator is thus computed as

$$s_1 = \sum_{i=1}^{N} \sum_{k=0}^{M_i} f_{r_{-y},k}^2 + f_{r_{-z},k}^2 + f_{l_{-y},k}^2 + f_{l_{-z},k}^2 \tag{3}$$

where $f_{\{r,l\}_{-y},k}$ and $f_{\{r,l\}_{-z},k}$ are respectively the force applied by the operator on the wooden part in the $-Y$ and $-Z$ direction at instant k. Subscripts r and l are respectively related to the right and left hands.

Operator reflexes – We observed in [5] that the appearance of accidental scenarios during the shaping process is strongly related to the craftsman's reflexes limits. Indeed, operators do not have the capacity to compensate for the sudden force variations caused by the disturbances sufficiently quickly [19]. The longer he takes to compensate for these forces and stabilize the workpiece, the more he will be in danger. For this reason we choose the stabilization time of the wood in response to a disturbance as a second safety criterion

$$s_{b2} \quad = \quad \sum_{i=1}^{N} t_{r_i} \tag{4}$$

where t_{r_i} represents the time taken by the velocity of the wooden part along the X-axis to get back within 10% of the its value at the end of trial i after a disturbance has been voluntarily generated in the trial.

3) Discomfort :

Operator force intensity – Several risk assessment methods relate the intensity of the forces applied by an operator in repetitive task to the appearance of musculoskeletal disorders [20]. It therefore seems obvious to consider that the greater the intensity of the forces exerted by the craftsman during the shaping process, the greater his discomfort. For this first criterion of discomfort, we consider only the intensity of the forces projected in the XY plan, which are related to the wooden part direction of motion

$$i_1 = \sum_{i=1}^{N} \sum_{k=0}^{M_i} f_{r_x,k}^2 + f_{r_y,k}^2 + f_{l_x,k}^2 + f_{l_y,k}^2 \tag{5}$$

where $f_{\{r,l\}_x,k}$ and $f_{\{r,l\}_y,k}$ are respectively the force applied by the operator on the wooden part in the X and Y direction (independently from their direction contrarily to indicator s_1) at instant k.

Postural discomfort – In the considered task, the major part of the wrenches provided by the operator is applied through his hands, which implies a strong solicitation of the wrists. According to the work developed in [21], beyond an extension of 30 degrees, the position of the wrist is no longer suitable for working with hand tools. So for this criterion of discomfort, we consider that if the extension of the wrist exceeds this angle the operator is in a state of discomfort. The indicator is given by

$$i_2 = \sum_{i=1}^{N} t_{d_i} \tag{6}$$

where t_{d_i} is the time spent by the operator in an uncomfortable posture during the i^{th} task completion.

In the following section we detail the application of these steps to a selected pilot task.

B. Physical Mock up / Mock up description

Given the accidental aspect of the task and the benefits cited in section II-C to use a mock up, we developed a physical realistic mock-up of the wood milling task in order to safely conduct the experiments and access all required measurements for the computation of the here-before introduced expertise indicators.

The mock up described in Figure 3 reproduces the process of a wood shaping task, where a 7 degree of freedom Panda collaborative robot from Franka Emika reproduces the cutting forces applied by the machine tool on the wooden piece accordingly to the model developed in [9] and accordingly to the implementation proposed in [5].

The Panda robot can be torque controlled with a control sampling frequency of $1kHz$. The reproduction of the cutting wrench can be obtained by choosing control torque $\boldsymbol{\tau}^c$ as:

$$\boldsymbol{\tau}^c = \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{J}(\boldsymbol{q})^T \boldsymbol{w}_s(\boldsymbol{p}_w) \tag{7}$$

where $\boldsymbol{q}$ is the generalized coordinates vector; $\boldsymbol{g}(\boldsymbol{q})$ is the gravity compensation torque; $\boldsymbol{J}(\boldsymbol{q})$ is the end-effector Jacobian matrix and $\boldsymbol{w}_s(\boldsymbol{p}_w)$ is the modeled cutting wrench, which depends on several parameters related to the wood type (density, wood grain...) and the cutting extension (number of teeth, diameter of the tool...). This parametric model allows to reproduce the sudden appearance of wooden nodes, which lead to sudden variations in the cutting forces. This phenomenon is considered by carpenters as possibly accidental given the difficulty of compensating that too sudden variation. Indeed, as mentioned in the previous section, their limited reflexes [19] and strength [22] may not be sufficient to instantaneously compensate for the unexpected increase/decrease in force. The motion of the wooden board being ideally performed at constant and rather low velocities, the use of a quasi-static model for the control of the robot is deemed sufficient given the expected level of accuracy of the simulated cutting wrenches.

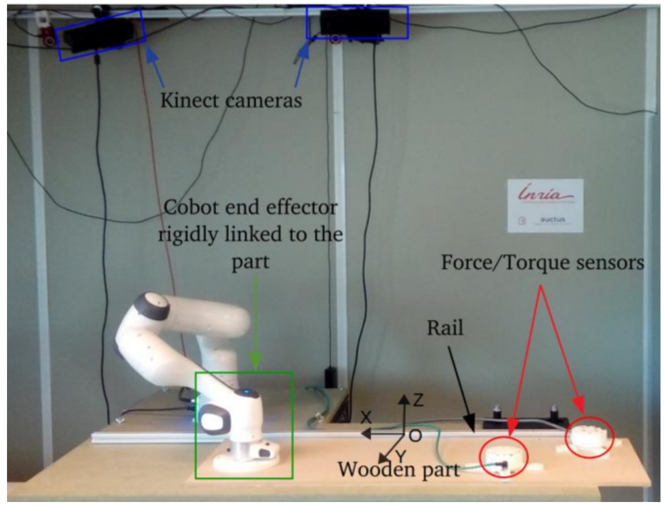

Fig. 3. Experimental mock-up including a table, a guiding rail, a wooden board, the a 7DoF Panda robot, two 6-axis F/T sensors and two RGBD Kinect cameras.

As shown in Fig. 2, the robot end-effector is rigidly linked to a wooden part, which is instrumented with two 6-axis force/torque sensors that measures the wrenches applied by the right and left hands of the subjects during the experiment. In addition, two RGBD Kinect cameras are mounted in order to measure the subject's articular angles.

C. Experimental protocol

Ten healthy male subjects are asked to move the wooden part along the rail at a constant speed via the force sensor handles. Two types of trials are then proposed:

- a standard trial where the cobot applies a constant cutting force of $-50N$ along the X-axis and $15N$ along the Y-axis on the wooden part throughout the trial.
- a disturbed trial where the cobot voluntarily vary the force in order to reproduce the effects of the appearance of a node. This disturbance is characterized by a sudden increase in cutting wrench at the node's entrance, going from $-50N$ to $-90N$ along the X-axis and from $15N$ to $25N$ along the Y-axis. When exiting the node, the cutting wrench instantaneously goes back to its nominal value. The generated node is $10cm$ long.

The experimentation is composed of three successive phases:

- **the initial phase** is composed 5 trials among which three are standard ones and two are disturbed ones. Before this phase, the subjects have no experience of the task.
- **the training phase** is composed of 20 trials. During this phase, we randomly separate the subjects into two groups of five people. The first group performs 10% of disturbed trials and 90% of standard trials, while the second group performs 50% of disturbed trials and 50% of standard trials.

- **the final phase** is similar to the initial phase.

Note that during the three phases no information is given to the subjects on the type of trials. It is only specified that there is a resistance when moving the wooden part and that this part has to be moved along the rail at constant speed from an initial position to a final one. All 30 trials are performed successively without any significant break between two trials of the same phase. A 30 seconds break is imposed between two phases.

Adjustment and normalization of the assessment criteria

In order to allow comparisons between subjects, all indicators for a given subject are normalized by their respective maximum value observed in the 30 trials. Moreover, for the sake of coherence, we transform some criteria to ensure that their score evolve in a coherent direction to assess the concerned dimension. For example, currently, a low value of the performance criteria indicates that the operator is efficient, but the opposite would make more sense (the higher a criterion value, the better). As a consequence, the complement to one of p_{b1}, p_{b2} and s_{b2} are considered instead of their original value:

$$p_1 = 1 - p_{b1} \tag{8}$$
$$p_2 = 1 - p_{b2} \tag{9}$$
$$s_2 = 1 - s_{b2} \tag{10}$$

IV. Results and discussion

The obtained results are presented in this section and analysed with the two following questions in mind:

- Does this approach allow to observe and analyze the handling strategy developed by the subjects?
- Is there an impact of training on this strategy?

A. Handling strategy analysis

Figure 4 provides, for each indicator/assessment criterion, the ratio between the initial phase (N=5) and the final (N=5) phase. These ratios are compared for the two considered groups. They are computed as follows

$$r_j = \frac{ac_{j\,initial}}{ac_{j\,final}} - 1 \tag{11}$$

where r_j is the ratio calculated for the assessment criterion j. ac_j represents successively $s_{1,2}$, $i_{1,2}$ and $p_{1,2}$.

We notice on Figure 4 an improvement of the two assessment criteria values related to task performance for the subjects of the first group (10% of disturbed trials during the training phase), as well as a positive evolution for one of the two safety criteria s_2, while the other one does not worsen. Regarding the discomfort, we observe that after training its assessment criteria values are clearly decreased.

Concerning the second group (50% of disturbed trials during the training phase), we observe that the values of both safety criteria increase significantly, particularly s_2. We observe that is also the case for values of the discomfort criteria, which increases less significantly than safety related assessment criteria. Concerning the task performance indicators, we notice that p_1 is constant, when p_2 decreases slightly.

Based on this observations, it can be noticed that after accumulating experience of the task completion, the two groups

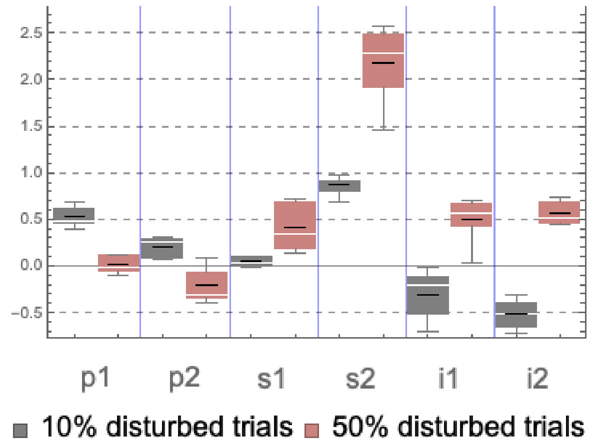

Fig. 4. This figure depicts the ratio between the final and initial phases of the experiment for the six assessment criteria of the two groups. It shows the mean value (black line) of the ratio for the 5 subjects in each group, its median value (white line), its 75% quantitative values (grey box for 10% disturbed group and dark pink box for the 50% disturbed group) and its maximum and minimum values (whiskers) for each ratio.

reconcile the dimensions of the triptych safety-discomfort-performance differently before and after the training phase, which, in our opinion, is the beginning of a handling strategy. Thus, the proposed approach allows to observe and analyze the manipulation strategy developed by the subjects.

B. Training impact

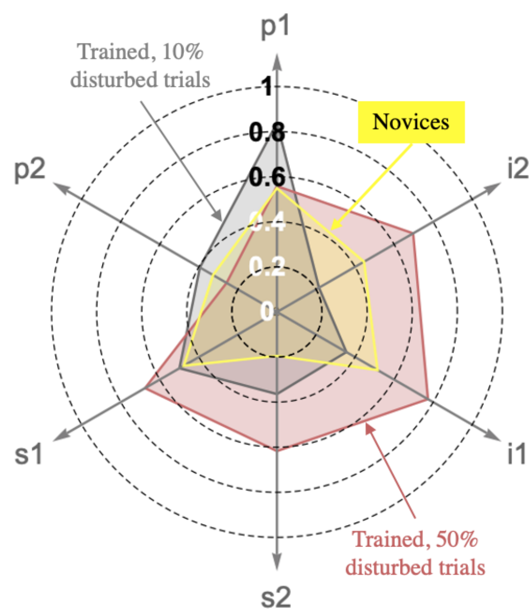

Fig. 5. This figure illustrates the distribution of the 6 assessment criteria for the novice phase in yellow and the final phase of the two groups, in red for the group that was trained with 50% of disturbed trials and in pink for the group that was trained with 10% of disturbed trials. The average of the criteria is plotted in all three cases: the average of the 10 subjects for the novice phase and the average of the 5 subjects in each group for the final phase.

From the observations made in the previous section, it was noticed that the values of the evaluation criteria evolve differently for the two groups. This is even more apparent in Figure 4, where we observe that subjects in group 2 (50% of disturbed trials during the training phase) increase the safety assessment criteria more significantly compared to the subjects in group 1 (respectively 19.8% for s_1 and 42.2% for s_2, compared to 2.1% and 16.94%). It is also interesting to observe the notable difference in the evolution of the discomfort assessment criteria for the two groups. The first group (10% of disturbed trials) reduces its discomfort (-15.9% for i_1 and -23.1%), unlike the group 2 that amplifies it (25.8% for i_1 and 25.16% for i_2). As for the performance criteria, they remain globally stable for the subjects in group 2 (1% for p_1 and -6% for p_2) but improves significantly for group 1, especially the time to complete the task criterion (28.9% for p_1 and 8.7% for p_2).

These observations allow us to distinguish two different handling strategy construction. The subjects in the first group tend to pay equal attention to the three dimensions of the safety-comfort-performance triptych and improve its aspects. While subjects in group 2 tend to pay special attention to safety and improve that aspect of the task completion at the expense of the discomfort aspect that deteriorates and of the performance one that does not improve. This is, in our opinion, the direct consequence of the higher frequency of disturbed trial occurrence during the training phase for group 2 subjects, which proves the impact of the training on the subject handling strategy.

V. Conclusion

In this work, we develop an approach to quantify manual expertise with the goal to better define this notion and improve its general understanding. This approach, validated experimentally, allows to deduce that an operator builds his handling strategy according to his experience of the task and based on the encountered training conditions. The evolution of this strategy is reflected by an evolution of the way the operator reconcile safety, discomfort and task performance.

These promising results open up a new way of thinking about the assistance provided by collaborative robots. Indeed, cobots are often considered as tools for addressing the improvement of one specific dimension of the task. However, cobots could actually provide a variable level of assistance depending on the level of experience of the operator. The provided assistance would aim at finding a personalized compromise among the considered dimensions of expertise, so that the improvement of one specific dimension does not alter others. This seems to be a necessary condition in order to preserve and improve the very specific manual expertise of each operator. In our opinion, this would bring a positive contribution to the acceptance of cobotic assistance in the industrial and handicraft sectors.

Future work will be dedicated to the application of this experimental protocol to more experienced operators. This should improve our understanding of the notion of expertise. Based on these new results, we will also focus on the development of an adaptive control framework that will modulate the behaviour of an assistive robot to the personal needs of each operator, in particular in order to improve the learning curve of novices in all dimensions of expertise.

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